Performance characteristics of ultra-narrow ArF laser for DUV lithography

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ABSTRACT

Today, commercial line-narrowed ArF lasers for Deep-UV lithography are typically producing spectral bandwidth of 0.6 pm FWHM. This value forces the stepper/scanner manufacturers to use large amount of CaF_2 in the lens design as well as fused silica in order to compensate for chromatic aberrations. We describe in this paper the parameters -such as pulse duration, fluorine concentration and divergence- which influence the line-narrowing efficiency of ArF lasers. We are also presenting results obtained using a new optical cavity design using an etalon as output coupler that provides bandwidth of 0.3 pm at FWHM and 0.8 pm for 95% of the energy, performance that could allow to greatly reduce the need for CaF_2.

1. INTRODUCTION

The optical properties, and particularly the dispersion, of fused silica are significantly different at 193 nm compared to 248 nm. This creates more stringent requirement for the laser source if one wants to reduce the effect of chromatic aberrations. An approximation of the Full-Width-at-Half-Maximum (FWHM) value of the laser spectrum needed in order to avoid chromatically corrected lenses is given by:

$$\Delta l_{FWHM} = \frac{(n-1)\, l}{f\,(1+m)(\frac{dn}{dl})\, NA^2}$$

For example, a lens of NA=0.7 requires a spectrum of 0.2 pm Full-Width-at-Half-Maximum (FWHM) for a 193 nm ArF laser while a 0.6 pm FWHM KrF laser is sufficient at 248 nm. The latter is available now but the typical bandwidth of commercial ArF lasers is only 0.6 pm forcing scanner and stepper manufacturers to use Calcium Fluoride to compensate for chromatic aberrations at 193 nm. In this paper, we describe the technical difficulties of the line-narrowing of an excimer laser, we show what are the requirements of the metrology tool for measuring both FWHM and the width containing 95% of the energy and present results obtained with a new technique that approaches the requirement of 0.2 pm FWHM.

2. DIFFICULTIES OF LINE-NARROWING

2.1 Physics

The general line-narrowing scheme we are using is shown on figure 1; it utilizes an echelle grating in combination with a prism-based beam expander. Among the characteristics of excimer lasers is their high gain and short pulse duration. As shown by the laser pulse shape, the number of round trips between the output coupler and the grating is only about three. That means that the number of pass through the line-narrowing element is small and put strong requirement on the "single-pass" line narrowing. We can approximate the requirement for a single trip bandwidth by:

$$\Delta l_f = \Delta l / n^{1/2}$$

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Therefore for a final bandwidth of 0.3 pm we must have a single trip linewidth of 0.5 pm.

2.2 Metrology

The FWHM is a very limited representation of the line shape of the laser and the width that contains 95% of the energy ($\Delta\lambda_{95\%}$) is a better representation of it. However, it is very difficult to predict the value of $\Delta\lambda_{95\%}$ based only on the FWHM. Figure 2 shows a typical ArF spectrum compared with three attempts of fitting it with conventional shapes: Gaussian, Lorentzian, Lorentzian at the power 3. None of those predicts the 95% with a good accuracy. In conclusion, the only way to know $\Delta\lambda_{95\%}$ is to use a high resolution spectrometer. Etalon spectrometer could give FWHM values with high resolution but fail providing any good 95% value due to their intrinsic line shape.
In order to accurately measure the $\Delta\lambda_{95\%}$ we have developed a high resolution double pass grating spectrometer with a theoretical slit function of 0.094 pm FWHM. The signal to noise ratio is less than 1/1000 which is necessary for achieving the desired precision in the 95% measurement.

3. PARAMETERS AFFECTING LINEWIDTH

3.1 Fluorine concentration

Even if it increases the laser efficiency (figure 3), the F2 concentration has a detrimental effect on bandwidth. By shortening the turn-on time of the laser emission, higher fluorine concentration has the effect of broadening the spectrum as shown by figures 4 and 5. The choice of optimum fluorine is the result of a trade off between best efficiency and narrower bandwidth.

3.2 Time resolved spectrum-effect of pulse duration and divergence

As shown in the previous paragraph, the time evolution of the laser power has a large influence on the spectrum. Figure 6 and 7 present measurements of the evolution of both $\Delta\lambda_{FWHM}$ and $\Delta\lambda_{95\%}$, during the lasing time. As expected, both start high due to the contribution of the portion of light that hasn't been more than once through the line narrowing module. More surprising is an increase of the 95% value at the end of the pulse. N. Lisi (ref. 1), has observed a similar effect on the divergence of long pulses excimer lasers, potentially due to late deterioration of the discharge leading to increased scattering of light. We have measured the time evolution of the divergence of our laser (figure 8) and found a late increase that follows closely the increase in bandwidth. The increase of the divergence has the effect of “filling” the tails of the spectrum, increasing the 95% value without noticeable change in the FWHM value.

4. ULTRA NARROW SPECTRUM WITH ETALON OUTPUT COUPLER

A modification to our present day line narrowing technology uses a low finesse etalon as an output coupler[2] . The figure 9 presents the principle of the Etalon Output Coupler compared with the classic scheme of an etalon-based line narrowed optical cavity. In the latter case, a high finesse etalon is placed inside the cavity, which causes high thermal stress, and needs the use of complex and life limited high reflective coatings. In the case of the EOC scheme, a low finesse uncoated etalon is used providing a maximum reflectivity of 15% and consequently decreasing a lot the intra-etalon power. The maximum reflectance of the etalon needs to be tuned to the maximum reflection of the grating. If needed, reflectivity of 30 % could be achieved using simple single layer coatings. This technique doesn't affect the overall efficiency of the laser and significantly reduces the bandwidth as shown on figure 10: with the EOC, we obtain a typical bandwidth of 0.3 pm FWHM and 0.8 pm for $\Delta\lambda_{95\%}$,. Those values are not deconvolved and thus can be considered slightly pessimistic. This new technique adds some complexity to the optical cavity but keeps the other laser parameters unchanged. The increase in cost of operation added by the Etalon Output Coupler is about 3% of the total cost. Figure 11 presents a comparison between the standard ArF laser cavity using a flat output coupler and the EOC. The time evolution of bandwidth shows that the minimum is

reached sooner in the case of the new technique. The late increase in the 95% is also less pronounced. Another very interesting property of this improved technology is that the bandwidth is 2.5 times less sensitive to fluorine concentration allowing much broader operating range.

5. CONCLUSION

By using the Etalon Output Coupler technique we have been able to reduce the bandwidth of an ArF laser down to 0.3 pm FWHM and 0.8 pm for 95% of the energy. This performance could allow stepper/scanner manufacturers to greatly diminish the amount of CaF2 used in 193 nm imaging lenses.

6. REFERENCES

1. N. Lisi, P. Di Lazzaro, F. Flora, *Optics Communications* **136**, pp. 247-252, 1997.
2. A. Ershov, U.S. Patent No. 5,856,991

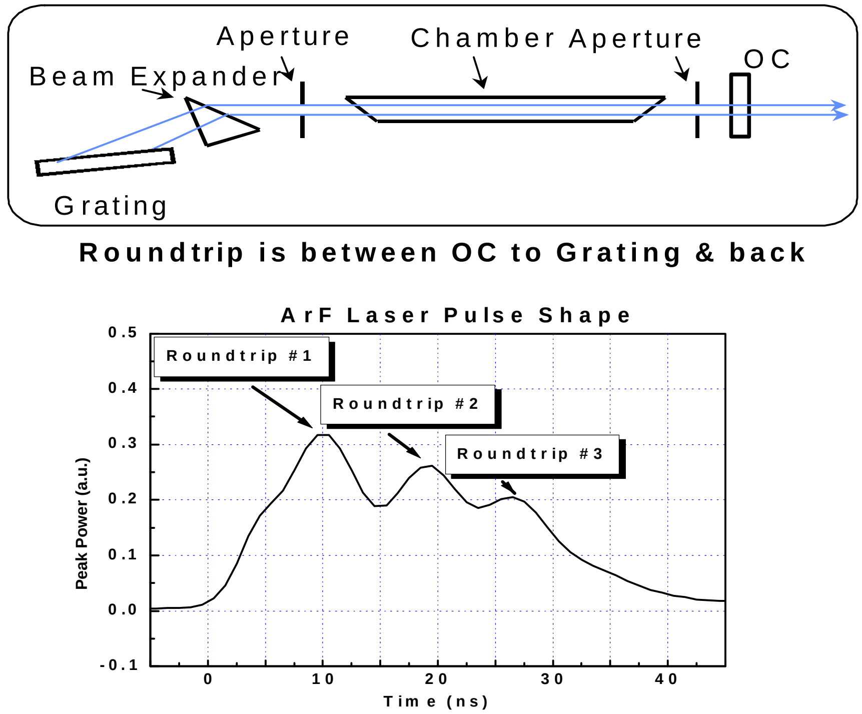


Fig. 1: Line-narrowing scheme and typical ArF pulse shape

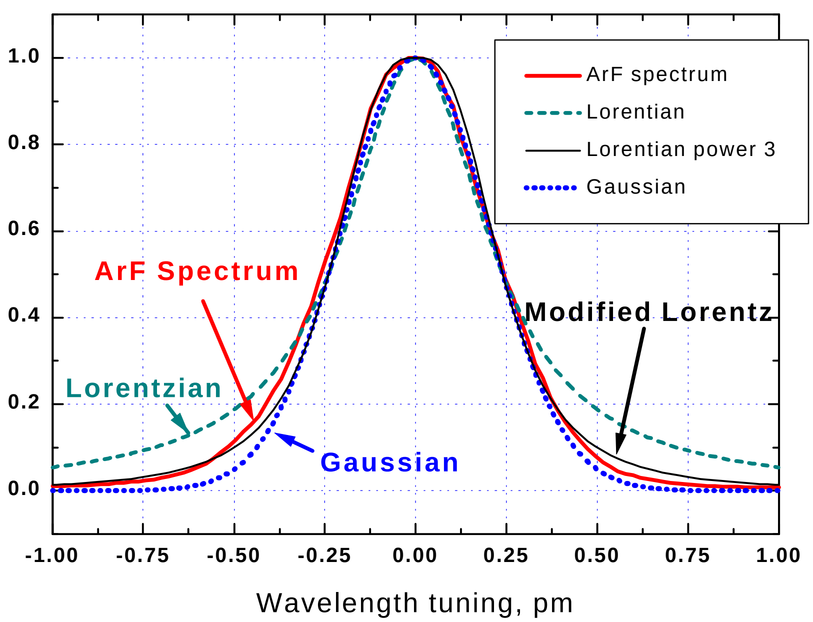


Fig. 2: Actual Arf spectrum compared with various standard shapes

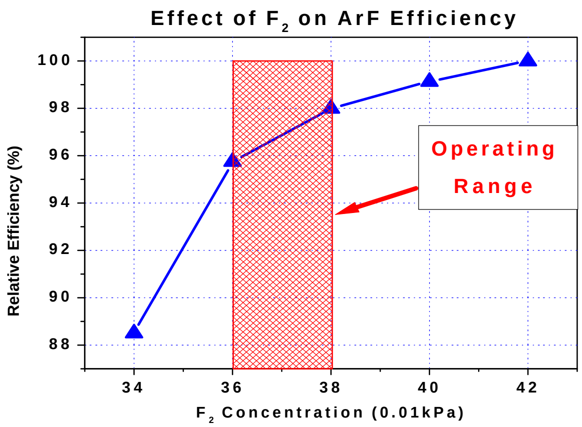


Fig. 3: Effect of F2 on efficiency

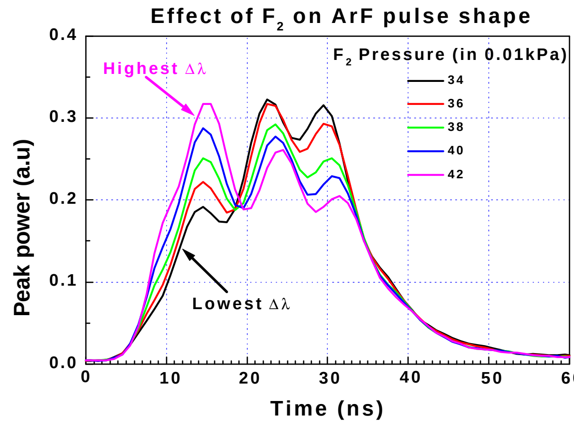


Fig. 4: Effect of F2 on pulse duration

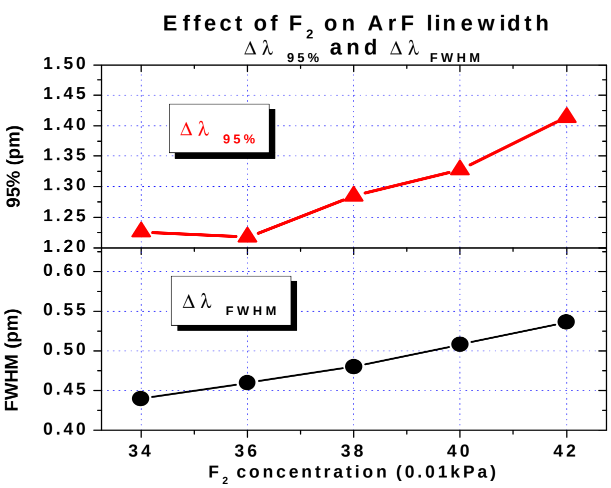


Fig. 5: Effect of F2 on bandwidth

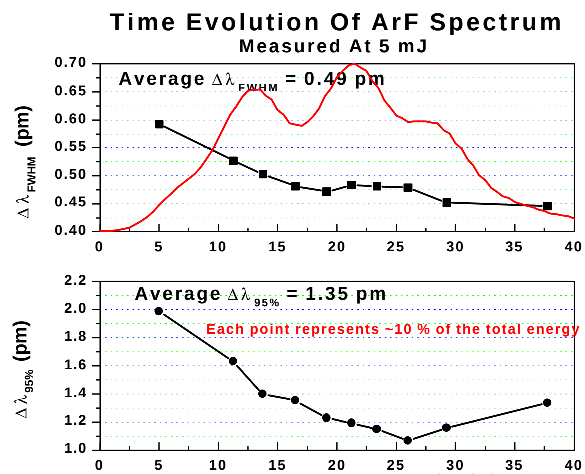


Fig. 6: Time evolution of spectral properties

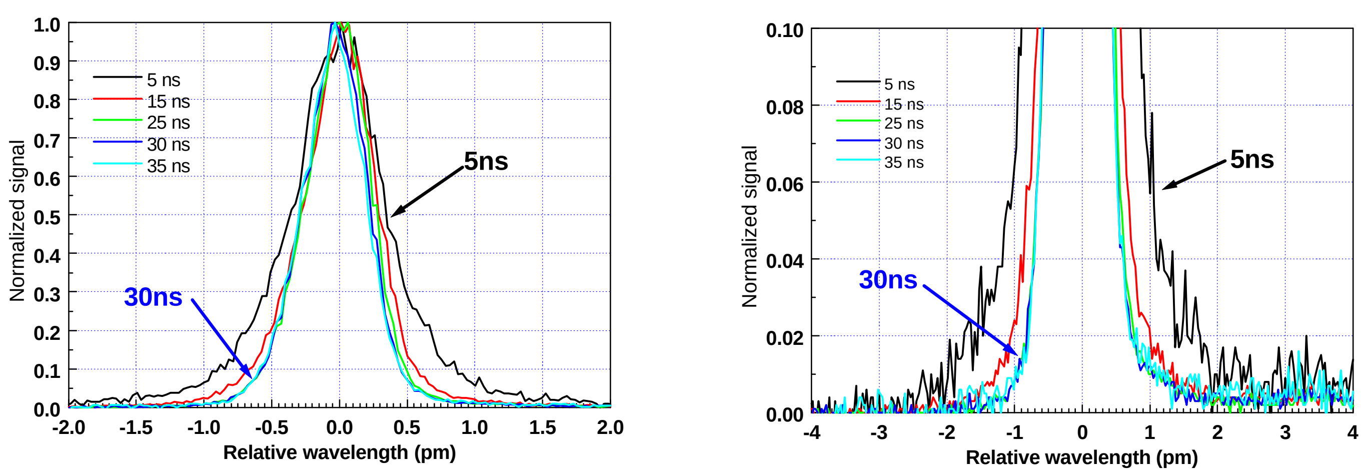


Fig. 7: Spectrum at different point in time

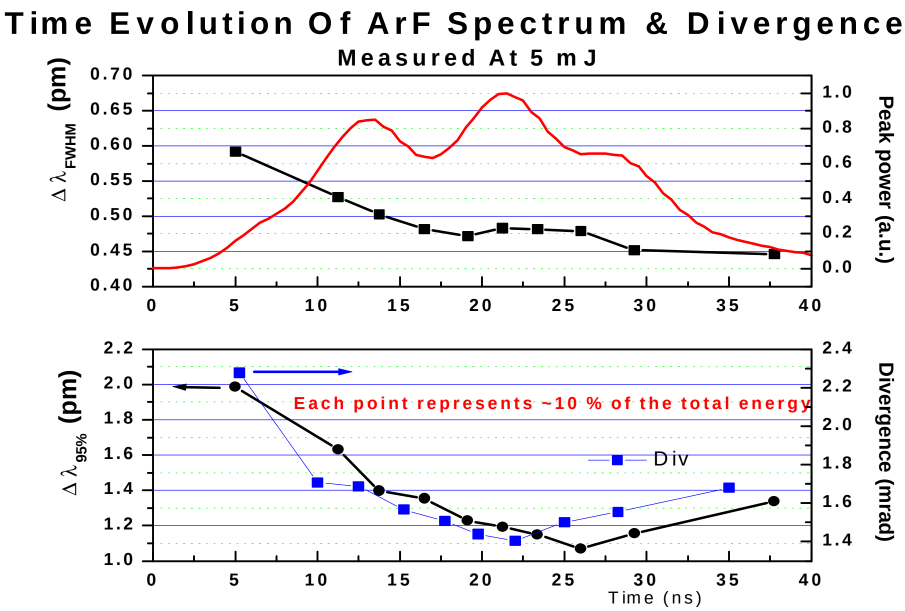


Fig. 8: Comparison of the time evolution of the beam divergence and bandwidth

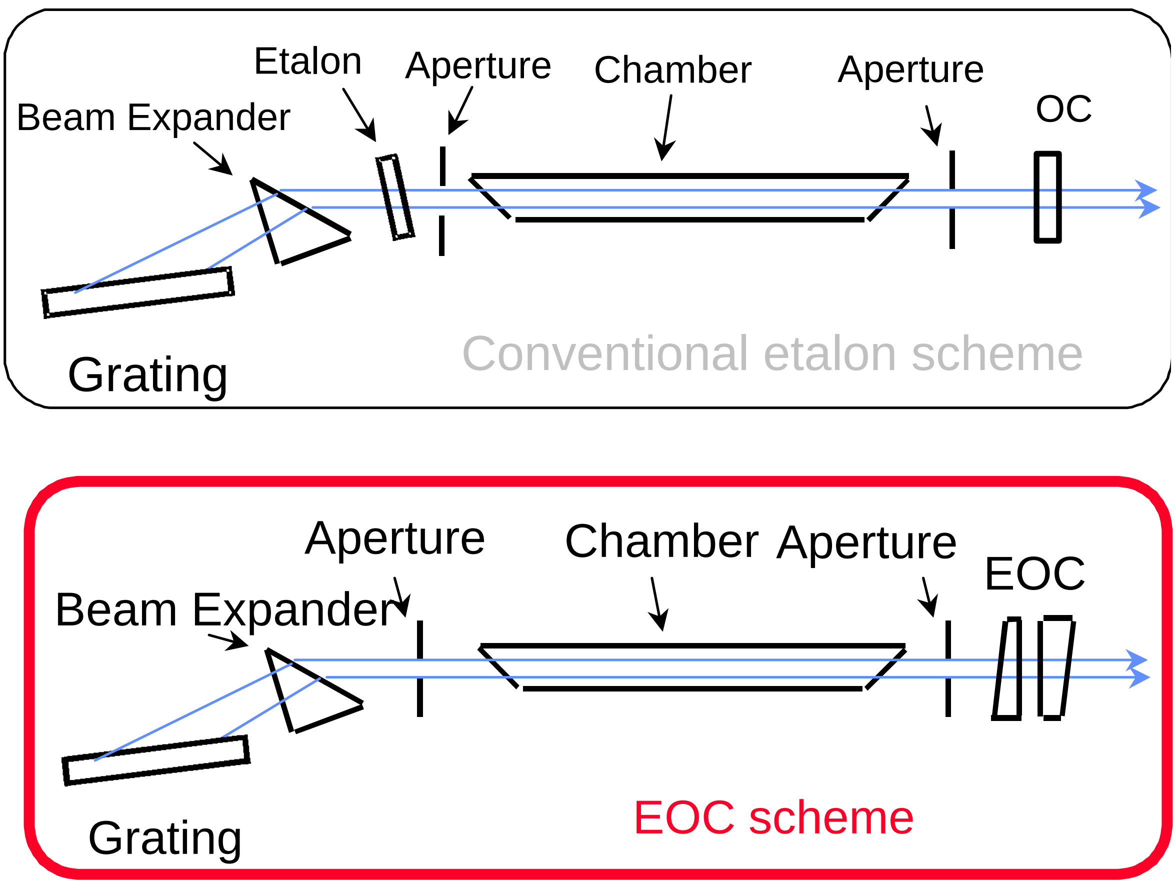
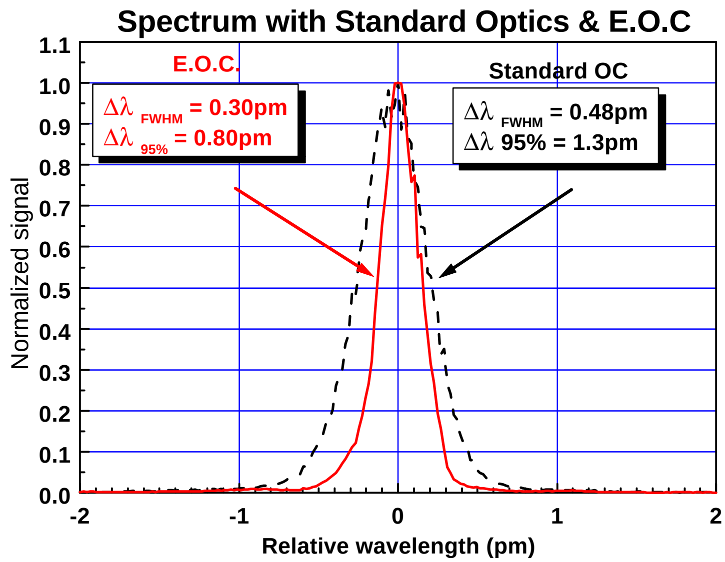


Fig.9: Etalon Output Coupler scheme



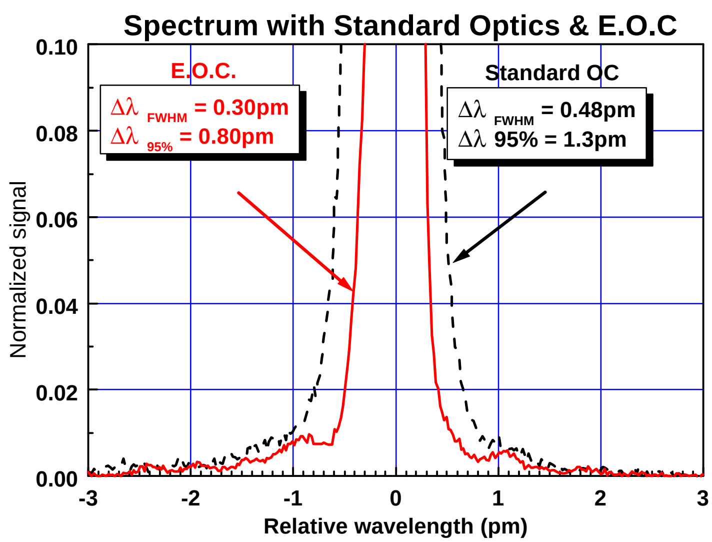
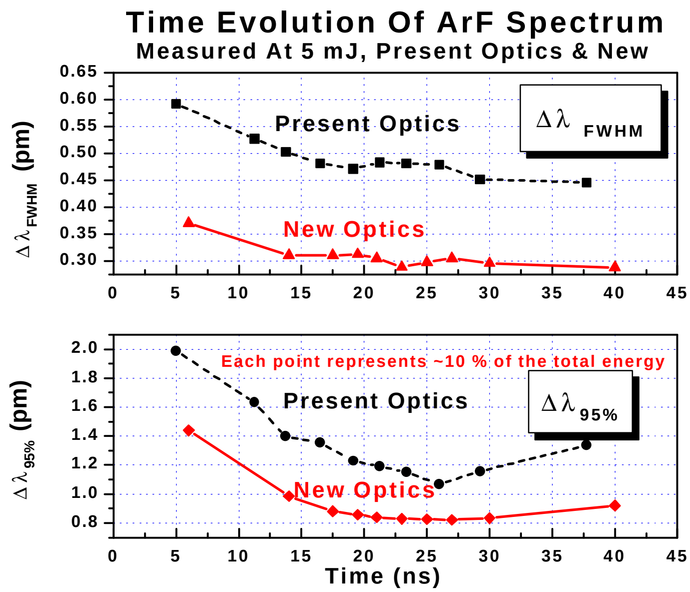


Fig.10: Comparison of the spectrum measured with a standard output coupler and the Etalon O.C.



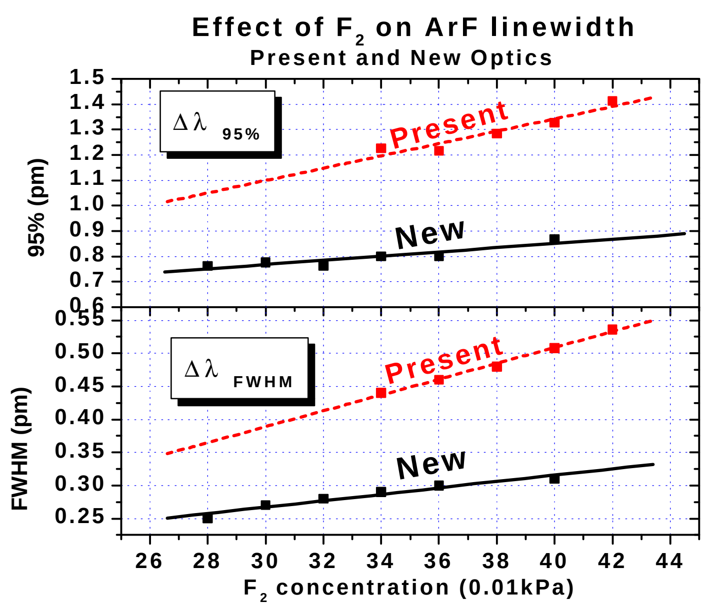


Fig.11: Time evolution of the spectrum and sensitivity to F2 for a standard OC and the EOC